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# MULTI-LOOP CONTROL DESIGN IN MULTIVARIABLE (2X2) CONTINUOUS STIRRED TANK REACTOR

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***Abstrak*** *-- Dalam penelitian ini, desain dan tuning multi-loop untuk multivariabel (2x2) CSTR dilakukan untuk mencapai kinerja kontrol CSTR yang optimal. Penelitian ini menggunakan reaktor Model Bequette dan software MATLAB dan diharapkan dapat mengatasi gangguan dalam reaktor sehingga sistem reaktor mampu menstabilkan dengan cepat meskipun gangguan. Dalam penelitian ini, desain dibuat menggunakan pendekatan multi loop, bersama dengan PI controller sebagai langkah berikutnya. Kemudian, BLT dan metode penyetelan auto-tune digunakan dalam PI controller dan diberi gangguan dari metode find tuning. Performa kontroler kemudian dibandingkan. Hasil dari penelitian ini menunjukkan bahwa dalam hal penolakan gangguan, BLT lebih baik dari auto-tune berdasarkan perbandingan antara kedua performa kontroler. Untuk IAE dalam kasus suhu, BLT adalah 30% lebih baik dari auto-tune, tapi hampir sama untuk kasus konsentrasi. Untuk settling time untuk kasus konsentrasi, BLT adalah 30% lebih baik dari auto-tune, dan untuk kasus suhu, BLT adalah 18% lebih baik dari auto-tune. Untuk waktu kenaikan untuk kasus konsentrasi dan temperatur, BLT adalah 30% lebih baik dari auto-tune.*

***Kata kunci*** *: Pendekatan Multi-loop, Bequette reactor, Performa Pengendali*

***Abstract*** *-- With this study, the design and tuning of multi-loop for multivariable (2x2) CSTR will be made in order to achieve optimum CSTR control performance. This study used Bequette model reactor and MATLAB software and is expected to be able to cope with disturbances in the reactor so that the reactor system is able to stabilize quickly despite the distractions. In this study, the design will be made using multi-loop approach, along with PI controller as the next step. Then, BLT and auto-tune tuning method will be used in PI controller and given disturbances to both of tuning method. The controller performances are then compared. Results of the study are then analyzed for discussions and conclusions. Results from this study have shown that in terms of disturbance rejection, BLT is better than auto-tune based on comparison between both of controller performances. For IAE for the case of temperature, BLT is 30% better than auto-tune, but it is almost the same for the case of concentration. For settling time for the case of concentration, BLT is 30% better than auto-tune, and for the case of temperature, BLT is 18% better than auto-tune. For rise time for the case of concentration and temperature, BLT is 30% better than auto-tune.*

***Keywors****: Multi-loop approach, Bequette reactor, Controller performances.*

## 1. INTRODUCTION

CSTR reactor is used in big industries that require processes that can't be stopped because the production has to remain continuous such as oil refineries and so on (Altmann, 2005). Usually in this type of reactor, the reaction occurs always not linear and has very high complexity. This kind of reaction is difficult to control by conventional method because it has multiple steady states in this equipment. Also reactor of this kind involves a multivariable system that's why even proportional-Integral (PI) control system may not give good results for multivariable systems. This kind of condition also led to frequent interruptions to the CSTR reactor that would make the resulting product does not fit with what is desired (Farouq and Jayakummar, 2009) (Wu, 2000).

That's also why it's necessary to have the control system that can work well in nonlinear and multivariable system. The approach will be used here is the multi-loop approach. Although it has been decades, there are already many successful multi-loop strategies have been used and proven to be a good approach thus it continue to be used. Because of its use of simple algorithms, it's ease to be understanding by plant operating personnel, which is the result of its simple control structure. Since each controller will use only one measured controlled variable and adjust only one manipulated variable, the actions of the controllers are relatively easy to monitor (Marlin, 2000).

This study will use a CSTR model with a cooling jacket (Bequette, 1998). The method used was based on multi-loop approach with a variety of disorders provision replaces variations of set point changes. The main interest here is how one can pair the right combination for each of manipulated and controlled variables, because the right pair of it will led to a better performances for a controller. The used reaction is exothermic irreversible first-order reaction with the multi-input multi-output (MIMO) 2x2 system. The success of this study will be tested by calculating the Integral Absolute Error (IAE) from the resulting BLT control design with PI control that is made then compared it with the value of the IAE from model with multi-loop control design PI control system on simulation program and comparison of the presence or absence of criterion performances for both of control systems (Fogler, 2006).

Objectives of this study are design and tuning the multi-loop control using PI controller for multivariable (2x2) CSTR in order to achieve optimum CSTR control performance. This study is expected to be able to cope with disturbances in the reactor so that the reactor system is able to stabilize quickly despite the distractions.

## 2. EXPERIMENTAL

The study began by making the material and energy balance for the system which is Bequette CSTR reactor then making the state space eq. in order to make the pairing between inputs and outputs of the system. Then design a PI controller system based on the pairing and tuning it using BLT PI tuning method, and calculate its controller performance. Compare the controller performance of PI with PI tuning from tuning software. Flow diagram of study in general can be seen in Figure 1.

This study uses a model of a non-isothermal CSTR reactor developed by Bequette, as the system to be controlled. (Bequette, 1998) and using a simulation software called MATLAB. This study will used multi-loop approach for PI tuning design (Chau, 2001).

Material used in this study is a model of CSTR (Bequette, 1998). The manipulated variables are feed concentration and initial temperature of cooling jacket. The controlled variables are the reactor temperature and the concentration of the product. The disturbance is what will happen when we change the manipulated variables. Reaction contained in this reactor is a simple reaction A → B. The assumptions used are the reaction A to B is a first order reaction.

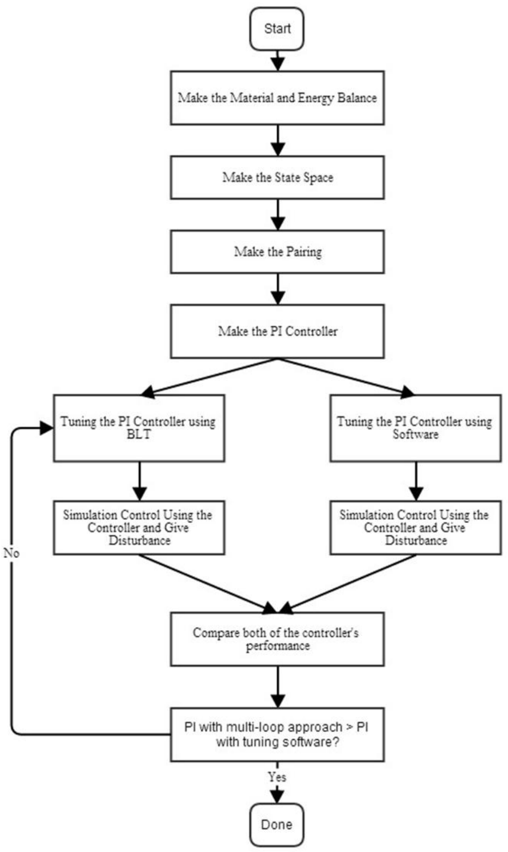


Figure 1. Flowchart

Here's a derivation model for the Bequette reactor. Equilibrium material in the reactor is shown by equation 1.

$$\frac{dV\rho}{dt} = F_{in}\rho_{in} - F_{out}\rho \quad (1)$$

With $\frac{dV\rho}{dt} = 0$ (amount of substances in the reactor remains constant), then equation 3.1 can be simplified to equation 2.

$$F_{out}\rho = F_{in}\rho_{in} \quad (2)$$

Density of the substance is also assumed to be constant, so it can be gotten the equation 3.

$$F_{out} = F_{in} = F \text{ dan } \frac{dV}{dt} = 0 \quad (3)$$

Because the reactor volume is constant, then the moles balance of component A can be written according to equation 4.

$$V\frac{dC_A}{dt} = FC_{Ai} - FC_A - rV \quad (4)$$

The reaction rate is shown by equation 5.

$$r = k_0 \exp\left(\frac{-\Delta E}{RT}\right) C_A \quad (5)$$

For the energy balance equation is shown in equation 6.

$$V\rho c_p \frac{dT}{dt} = F\rho c_p(T_i - T) + (-\Delta H)Vr - UA(T - T_j) \quad (6)$$

Final differential equations to calculate the concentration of the product and the reactor temperature is shown by equations 7 and 8:

$$\frac{dC_A}{dt} = \frac{F}{V}(C_{Ai} - C_A) - k_0 \exp(\frac{-\Delta E}{RT})C_A \quad (7)$$

$$\frac{dT}{dt} = \frac{F}{V}(T_i - T) + \left(-\frac{\Delta H}{\rho c_p}\right) k_0 \exp\left(\frac{-\Delta E}{RT}\right) C_A - \frac{UA}{V\rho c_p}(T - T_j) \quad (8)$$

Reactor parameters used in equations 7 and 8 are shown by Table1 (Bequette, 1998).

Table 1. Parameter Value Reactor Model

| Parameter | Value |
|---|---|
| F/V, $hr^{-1}$ | 1 |
| $k_0$, $hr^{-1}$ | 9703*3600 |
| (-ΔH), kcal/kgmol | 5960 |
| ΔE, kcal/kgmol | 11843 |
| ρcp, kcal/($m^3$K) | 500 |
| Tf, K | 298 |
| $C_{Ai}$ , kgmol/$m^3$ | 10 |
| UA/V, kcal/($m^3$K hr) | 150 |
| Tj, K | 298 |

**Study Procedures**

In order to make the pairing, first material and energy balance of the system need to be made because they will be used to find the state space of the system. The material and energy balance are from last eq.

$$\frac{dC_A}{dt} = \frac{F}{V}(C_{Ai} - C_A) - k_0 \exp(\frac{-\Delta E}{RT})C_A \quad (9)$$

$$\frac{dT}{dt} = \frac{F}{V}(T_i - T) + \left(-\frac{\Delta H}{\rho c_p}\right) k_0 \exp\left(\frac{-\Delta E}{RT}\right) C_A - \frac{UA}{V\rho c_p}(T - T_j) \quad (10)$$

Find the state space by converting the previous equation into:

$$F = \frac{dC_A}{dt} = \frac{F}{V}(C_{Ai} - C_A) - k_0 \left(\frac{-\Delta E}{RT}\right) C_A \quad (11)$$

$$G = \frac{dT}{dt} = \frac{F}{V}(T_i - T) + \left(-\frac{\Delta H}{pcp}\right) k_0 exp\left(\frac{-\Delta E}{RT}\right)(T - T_j) \quad (12)$$

Make the derivative equation based on the previous equation, for A and B, according to the state space formula:

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{Bu} \quad (13)$$

$$\boldsymbol{y} = \boldsymbol{Cx} + \boldsymbol{Du} \quad (14)$$

The derivatives:

$$A_{11} = \frac{dF}{dC_A} = -\frac{F}{V} - k_0 exp\left(\frac{-\Delta E}{RT}\right) \quad (15)$$

$$A_{12} = \frac{dF}{dT} = -k_0 \frac{\Delta E}{RT^2} exp\left(\frac{-\Delta E}{RT}\right) C_A \quad (16)$$

$$A_{21} = \frac{dG}{dC_A} = \left(-\frac{\Delta H}{\rho C_b}\right) k_0 exp\left(\frac{-\Delta E}{RT}\right) \quad (17)$$

$$A_{22} = \frac{dG}{dT} = -\frac{F}{V} + \frac{-\Delta H}{\rho C_p} k_0 \frac{\Delta E}{RT^2} C_A exp\left(\frac{-\Delta E}{RT}\right) \quad (18)$$

$$B_{11} = \left(\frac{dF}{dC_{Ai}}\right) = 1 \quad (19)$$

$$B_{12} = \frac{dF}{dT_i} = 0 \quad (20)$$

$$B_{21} = \frac{dG}{dC_{Ai}} = 0 \quad (21)$$

$$B_{22} = \frac{dG}{dT_i} = 1 \quad (22)$$

•

For C and D on the state space formula, C is using the matrix identity because the output is the state variable and since the C is the state variable, just use zero matrix for D

$$C = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad (23)$$

$$D = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \quad (24)$$

Make the pairing between the inputs and the outputs of the system.

Find the transfer function using MATLAB (commands can be seen at appendices)

By using the

[x,y]=ss2tf(a,b,c,d,1),

[x,y]=ss2tf(a,b,c,d,2) command and

g =tf(x(1,:),y),

i =tf(x(2,:),y)
the transfer function can be found. Result of the transfer function

$$G_{11(s)}=\frac{s+0.234}{s^2+1.404s+0.4469} \quad (25)$$

$$G_{12(s)}=\frac{2.02}{s^2+1.404s+0.4469} \quad (26)$$

$$G_{21(s)}=\frac{-0.0857}{s^2+1.404s+0.4469} \quad (27)$$

$$G_{22(s)}=\frac{s+1.17}{s^2+1.404s+0.4469} \quad (28)$$

Using the transfer function, find the $\lambda_{11}$ (pairing constant) using below equation. To find the value of K (gain), use MATLAB (commands can be seen at appendices)

$$\lambda_{11}=\frac{1}{1-\frac{K_{12}K_{21}}{K_{11}K_{22}}} \quad (29)$$

Use the step command to find each gain of the transfer function, by plotting it and measure the value of the amplitude until the graph is steady.

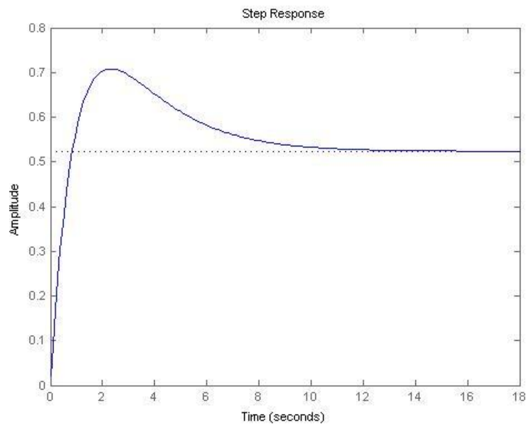


Figure 2. Gain ($K_{11}$)

The graph steady at 0.51; means the value of $K_{11}$ = 0.51.

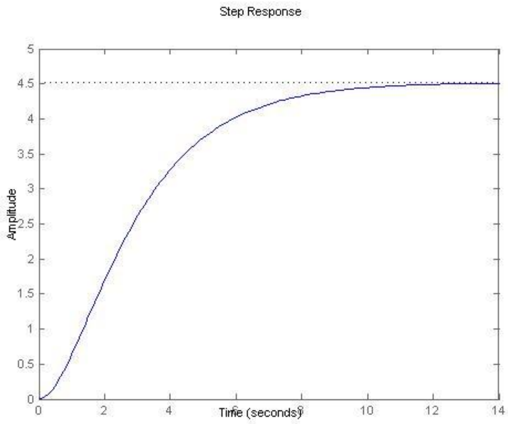


Figure 3. Gain ($K_{12}$)

The graph steady at 4.5; means the value of $K_{12}$ = 4.5.

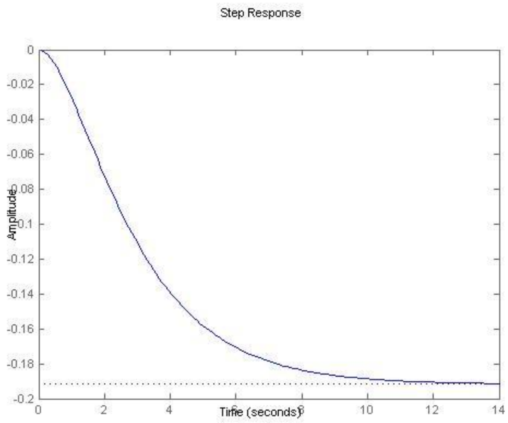


Figure 4. Gain ($K_{21}$)

The graph steady at -0.19; means the value of $K_{21}$ = -0.19.

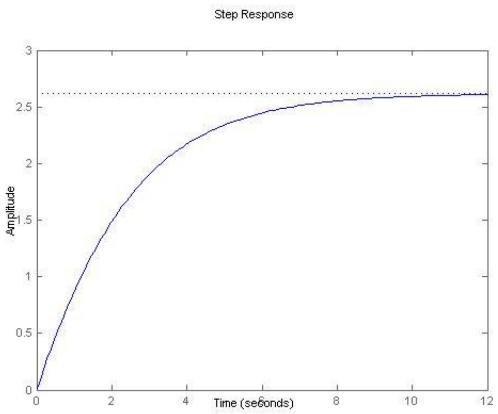


Figure 5. Gain ($K_{22}$)

The graph steady at 2.6; means the value of $K_{21}$ = 2.6.

Find the RGA by using the table below, thus the correct pairing for the system will be known (pick the combination that the number of it close to 1). The calculation will be:

$$\lambda_{11} = \frac{1}{1-\frac{(4.5)(-0.19)}{(0.51)(2.6)}} = 0.608 \qquad (30)$$

The array will be:

Table 2. Array of Pairing

| | $MV_1$ | $MV_2$ |
|---|---|---|
| $CV_1$ | $\lambda_{11}$ | $1-\lambda_{11}$ |
| $CV_2$ | $1-\lambda_{11}$ | $\lambda_{11}$ |

Thus the results are:

Table 3. Result of Pairing

| | $MV_1$ | $MV_2$ |
|---|---|---|
| $CV_1$ | 0.608 | 0.392 |
| $CV_2$ | 0.392 | 0.608 |

Thus the result is pairing between controlled variable 1 with manipulated variable 1 and controlled variable 2 with manipulated variable 2. Make the PI controller.

Tuning for BLT, using the Kc and $\tau_i$ from Ziegler Nichols, we can determine the Kc and $\tau_i$ of BLT by dividing the Kc with F and multiplying $\tau_i$ with F. the F value for this system is 1.65 and Kc = 8.63 and $\tau_i$ = 0.4 for temperature variable whereas Kc = 5.9 and $\tau_i$ = 1.515 for concentration variable. We get the Kc = 5.23 and $\tau_i = 0.66$ for temperature, and for concentration the Kc value is 3.57 and $\tau_i = 2.499$

As for the auto-tune, we can use auto-tune from software. Press the tune button then tune the PI controller.

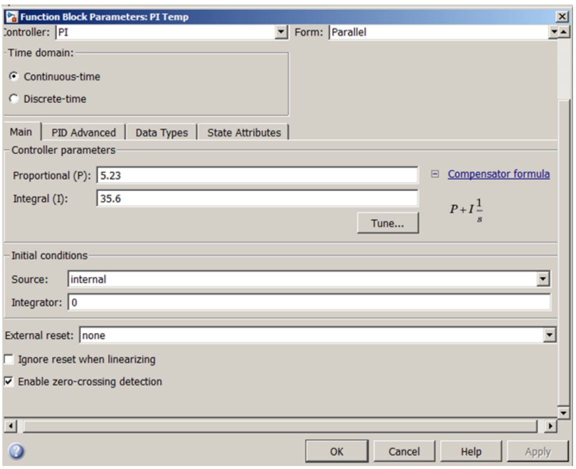


Figure 6. Auto Tune

Do the simulation control to $C_A$ and T using both controllers; also give disturbance with the same amount of it. From this simulation we can get response graph of CV, and can be calculated the IAE value for each simulation control using this eq.:

$$IAE = \int |SP(t) - CV(t)|\, dt \qquad (31)$$

We can see from the graph that, IAE is absolute area from the difference between graph areas of set point with graph area of CV response. The smaller the IAE means that CV is getting closer to its set point which means that the controller used is a good one. As shown in the example of response graph of CV, and the red area is the magnitude of IAE (Integral Absolute Error).

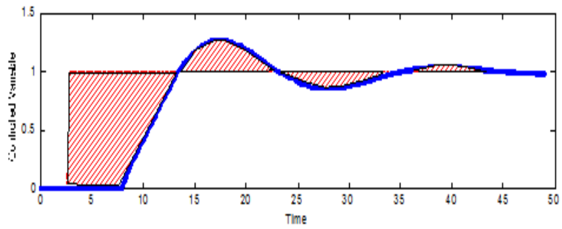


Figure 7.. IAE

For others controller criteria, after the graph is made, we can see from the graph to determine the good criteria for those controller performance by simply looking at the graph then see if the criteria is already good or not as the controller performance.

## 3. RESULTS

Reactor model used in this study is the MIMO system with size 2x2, and the study variables are 2 independent variables / input variables which are feed concentration, initial temperature of cooling jacket. And the 2 dependent variables / output variables which are the reactor temperature and the concentration of the product. In this study, the manipulated variable or independent variable is the factor that will be changed in an experiment. So the manipulated variables will be feed concentration and initial temperature of cooling jacket. And controlled variables are the variables that are input into the control system which the researcher holds constant (controls) during an experiment. So the controlled variables will be reactor temperature and concentration of the product.

Basically, the controlled variables need to be constant because that means the reactor is at steady state condition, and the product will not be interrupted by disturbances. That's why in order to control it; the manipulated variables will be changed. Based from the pairing method for multi-loop approach it can be determined that the change of input temperature or input concentration will only affect the output of them, respectively. This is because the pairing constant or $\lambda_{11}$ is simplified, so it can be safely assume that it is close to 1, means that the interaction between the temperature and the concentration can be neglected, respectively, or there are almost no interaction between them, so it can be safely assume that the tuning for this system can be done separately. $\lambda_{11}$ itself is a relative gain and it can be defined as ratios of open-loop to closed loop gain. This number is important because it is determining whether the system can be tuned correctly or not. Thus, great accuracy is required in calculating the relative gain. Changes made to the magnitude of Ti, Tc, and CAi is a reduction of 30%, 50%, and 70% and the addition of 30% of the initial value of them. These values have been assumed to represent the entire range of those variables.

The reactor will be controlled by the PI controller, and the manipulated variable will be inlet concentration and input temperature. Figure 8 is about Bequette reactor and Figure 9 is about the reactor after given the controller.

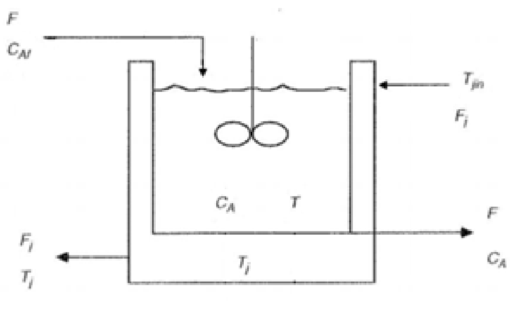


Figure 8. Bequette Reactor

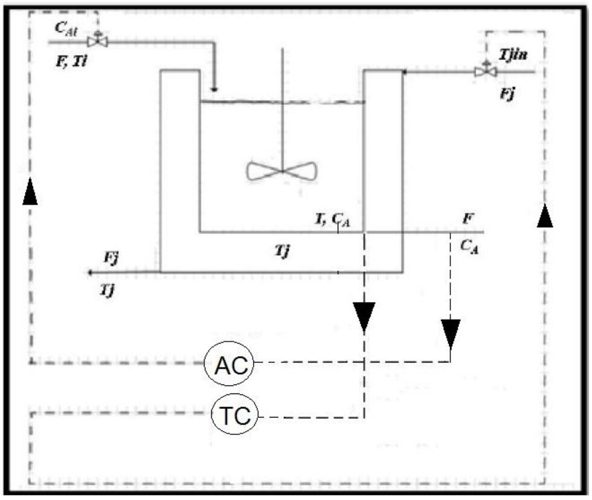


Figure 9. Multi-loop Reactor control after pairing

For Figure 10, those are about design of the system after given controller in MATLAB software. It is then given disturbances and change of set point in order to be analysed whether the controller is good or not.

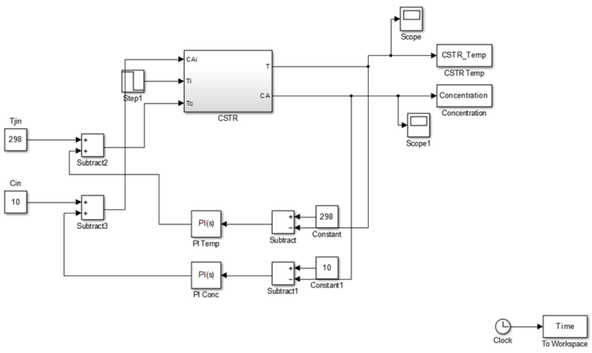


Figure 10. Disturbance Using Simulink (change of Ti)

For the change of Ca and Tc, the only different is the step input is at Ca and Tc before the PI controller.

Comparator used in this study is the PI controller between the one that using the multi-loop approach with BLT method, and the one that using the auto-tune. PI controller will do the handling of the disturbance, which will then be compared with each other. The structure of the PI controller used is a multi-loop control, in other words when the disturbance is given, there's a chance that both of the inputs will be affected as well as the outputs. The result of it can be seen in the following tables and figures. For Table 4.3 to 4.5 is about the comparison of both PI tuning method's IAEs.

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Table 4. Comparison of BLT PI's IAE and PI's (auto-tune) IAE on concentration and temperature control (Ti change)

| Disturbance (%) | T (Auto-tune) (K) | C (Auto-tune) ($kgmol/m^3$) | T (BLT) (K) | C (BLT) ($kgmol/m^3$) |
|---|---|---|---|---|
| -30 | 101.53 | 0.44 | 22.77 | 0.60 |
| -50 | 163.45 | 0.49 | 32.64 | 0.66 |
| -70 | 225.37 | 0.53 | 42.00 | 0.71 |
| +30 | 101.73 | 0.72 | 25.08 | 0.73 |

Table 5. Comparison of BLT PI's IAE and PI's (software) IAE on concentration and temperature control (Ca change)

| Sp Change (%) | T (Auto-tune) (K) | C (Auto-tune) ($kgmol/m^3$) | T (BLT) (K) | C (BLT) ($kgmol/m^3$) |
|---|---|---|---|---|
| -30 | 11.40 | 104.10 | 7.85 | 104.92 |
| -50 | 13.17 | 173.42 | 8.08 | 174.58 |
| -70 | 14.93 | 242.75 | 8.30 | 244.23 |
| +30 | 11.53 | 104.04 | 7.98 | 104.91 |

Table 6. Comparison of BLT PI's IAE and PI's (software) IAE on concentration and temperature control (Tc change)

| Sp Change (%) | T (Auto-tune) (K) | C (Auto-tune) ($kgmol/m^3$) | T (BLT) (K) | C (BLT) ($kgmol/m^3$) |
|---|---|---|---|---|
| -30 | $\mathbf{3.025 \times 10^3}$ | 0.45 | $\mathbf{3.125 \times 10^3}$ | 0.58 |
| -50 | $\mathbf{5.03 \times 10^3}$ | 0.45 | $\mathbf{5.20 \times 10^3}$ | 0.58 |
| -70 | $\mathbf{7.035 \times 10^3}$ | 0.45 | $\mathbf{7.28 \times 10^3}$ | 0. 58 |
| +30 | Unstable | Unstable | Unstable | Unstable |

For Figure from 11 to 12 those are about the response of the output after given disturbances. In this case, the disturbance is change in Ti. It can be seen that the trend of the graph is following the change in Ti, for example if the change is -30% of Ti, then the disturbance peak will go up then down a bit, but if the change is +30%, then the peak will go down then up.

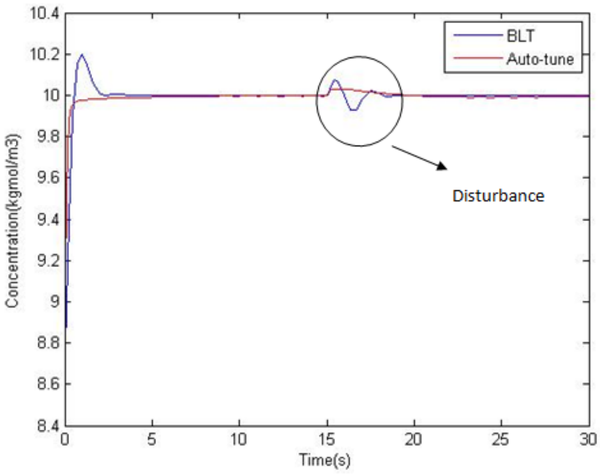


Figure 11. Response of concentration caused by ΔTi = -30%

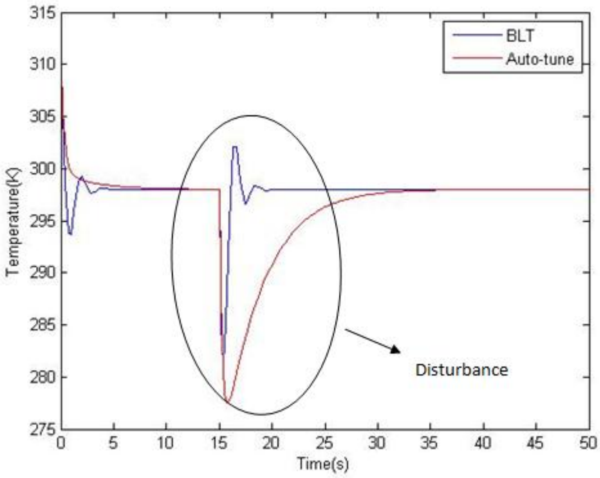


Figure 12. Response of temperature caused by ΔTi = -30%

Overall criterion performances of the system suggest that BLT approach is a better method than auto-tune. For the settling time, BLT suggests a faster response in reaching the system's steady state condition, despite of the overshoot and the decay ratio is there. In summary, the smaller the number in criterion performances, then the faster the response of a controller.

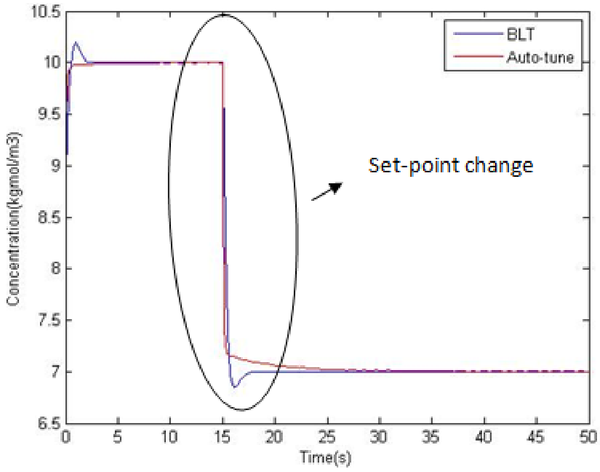


Figure 13. Response of concentration caused by $\Delta C_A$ = -30%

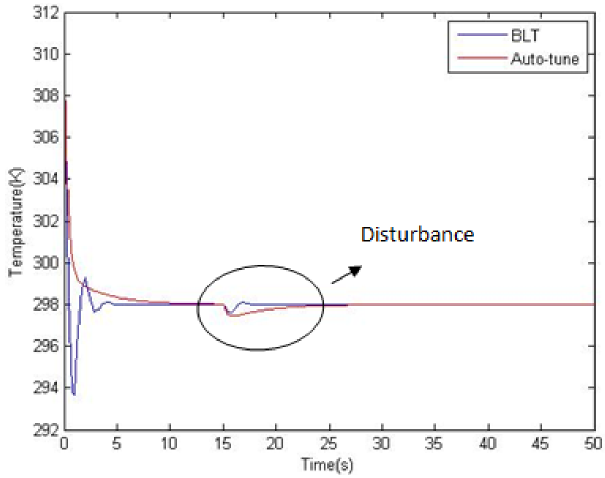


Figure 14. Response of temperature caused by $\Delta C_A$ = -30%

For Figure 13 to 14, those are about the set point change. It is shown that BLT and auto-tune method has almost the same results in terms of criterion performances. Even though, BLT has a slightly better criterion performance than auto-tune in terms of settling time. Settling time is important because the system has to reach its steady state as fast as it can be, after receiving disturbances or the change in set-points, in order to maintain the product of the reactor.

For Figure 15 to 16, those are about the set point change in Tc, same with previous set-point change, it can be seen that because there is a change in set point, that causes disturbance in the concentration. It is on purpose in order to know the response of the controllers.

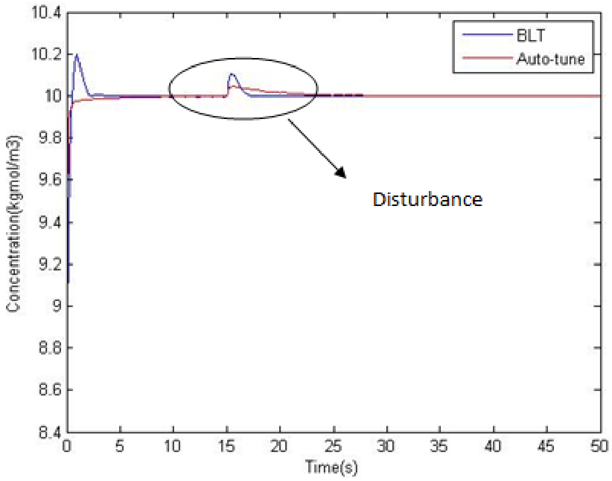


Figure 15. Response of concentration caused by $\Delta Tc$ = -30%

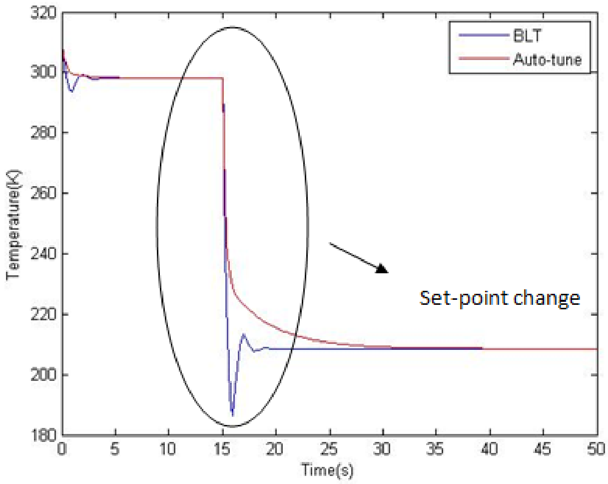


Figure 16. Response of concentration caused by $\Delta Tc$ = -30%

Simulations conducted in this study are essentially making multiloop control and is used to handle a given disorder in the system. In this study, given the disruption to the system in the form of steps. Disruptions in the system are disturbance (change in Ti) and set-point change (Ca and Tc). Then BLT capabilities that have been made will be compared with the PI in the tuning software capabilities in dealing with the same disorder. For IAE for the case of temperature, BLT is 30% better than auto-tune, but for the case of concentration, BLT and auto-tune is almost the same. For settling time for the case of concentration, BLT is 30% better than auto-tune, and for the case of temperature, BLT is 18% better than auto-tune. For rise time for the case of concentration, BLT is 30% better than auto-tune, and for the case of temperature, BLT is 30% better than auto-tune.

For decay ratio for the case of both concentration and temperature, auto-tune is better than BLT because auto-tune doesn't have decay ratio. Auto-tune and BLT doesn't have offset for the case of both concentration and temperature. For overshoot for the case of both concentration and temperature, auto-tune is better than BLT because auto-tune doesn't have decay ratio. It can be seen from the criterion performances, for the BLT control design, each of them has a better value than the PI that using the auto-tune, especially from the offset on the temperature of PI that using the tuning software. It means that the value of it will never reach the set point given in the system. It may control it but it will not give the same performance as the BLT control because of it. But the offset is so small it can be neglected, it just affected the settling time. It will get longer to settle after rejecting the disturbances. That is why the IAEs of auto-tune are bigger than BLT.

The BLT control also has a faster response on controlling the system, proven by the value of the settling time on the concentration and the temperature. It is also proven to have a better performance because of the value of the rise time for the concentration and the temperature is much faster for BLT design rather than the one using the software. Although for set-point change Tc for +30% of initial value, even the BLT couldn't handle the system when its set point is change. It means that the PI controller couldn't handle the disturbance or already reach its limit. The auto-tune works by processing feedback information in the form of error generated. Also auto-tune works by "fulfilling" all the criterion performances, like no decay ratio or overshoot.

That's why the response became too long and it takes longer time to reach steady state condition after received disturbances. Whilst for BLT, the detuning factor is adjusted so that the biggest log modulus, which is a measure of how far the system is from closed-loop instability, has a specified value. That's why this method provides reasonable preliminary controller settings with guaranteed closed-loop stability. The detuning factor is needed because of the Ziegler-Nichols method earlier used is causing the response to be too oscillatory and it causes low robustness. Therefore one needed to detune the controller to obtain a more stable response and increased robustness.

The controller will be less oscillatory and more tolerant to changes in process characteristic. So in conclusion, the BLT control design is proven to be better than the auto-tune because it's considering things that will help the controller to be a better one, for example the robustness.

## 4. CONCLUSIONS

Based on the result and discussion, it can be conclude that:

1. After doing pairing analysis, design of multi-loop control for multivariable (2x2) CSTR is output temperature ($CV_1$) paired with input temperature ($MV_1$), and output concentration ($CV_2$) paired with input concentration ($MV_2$).
2. Tuning results for BLT are for temperature loop, Kc = 5.23 and $\tau_i = 0.66$, and for concentration loop, Kc = 3.57 and $\tau_i = 2.499$ with the control performance parameters are better than the auto-tuner.
3. For IAE for the case of temperature, BLT is 30% better than auto-tune, but for the case of concentration, BLT and auto-tune is almost the same. For settling time for the case of concentration, BLT is 30% better than auto-tune, and for the case of temperature, BLT is 18% better than auto-tune. For rise time for the case of concentration, BLT is 30% better than auto-tune, and for the case of temperature, BLT is 30% better than auto-tune. For decay ratio for the case of both concentration and temperature, auto-tune is better than BLT because auto-tune doesn't have decay ratio. Auto-tune and BLT doesn't have offset for the case of both concentration and temperature. For overshoot for the case of both concentration and temperature, auto-tune is better than BLT because auto-tune doesn't have decay ratio.

**Notation List**

| | |
|---|---|
| T | Temperature (K) |
| C | Concentration (kgmol/$m^3$) |
| Sp | Set-point |
| CV | Controlled Variable |
| MV | Manipulated Variable |
| PI | Propotional-Integral |

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